Cetaceans and Naval Sonar: Behavioral Response as a Function of Sonar Frequency

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LONG-TERM GOALS

Data on the responsiveness of free-ranging cetaceans to mid-frequency sonar signals are lacking, with only a few species having been studied in relation to a few types of sonar signals, mostly SURTASS-LFA (Nowacek et al., 2007). This specific project was initially motivated by observations of possible killer whale (*Orcinus orca*) reactions to sonars, in the Vestfjord basin of Norway (Kvadsheim et al., 2007) and the USS Shoup incident in Haro Strait in Washington State (NMFS-NOAA report, 2005). While those incidents have not led to observation of strandings or direct mortality, the perceived behavioral changes in response to sonar have negatively impacted the public image of the Navies involved, and may have harmed the stakeholder community that works with killer whales. The high public profile of killer whales and the overlap of their habitats with operational areas make it likely that incidents will continue to occur worldwide. The killer whale population involved in the USS Shoup incident has been listed as endangered under the Federal Endangered Species Act, which increases the importance of establishing safe guidelines for sonar operations in killer whale habitat.

The Norwegian Navy with cooperation from the Netherlands Navy funded a pilot project in 2006 to assess the effects of sonar on killer whales, with PI Patrick Miller leading the whale tagging and behavior observation team (Kvadsheim et al., 2007). During that research trial the research team: 1.) observed whale presence in the Vestfjord basin in relation to a schedule FLOTEX ASW exercise, and 2.) experimentally exposed killer whales tagged with Dtags to sonar signals at different frequency bands. For the observational component of the pilot study, we found that following the start of a FLOTEX ASW exercise, killer whales that had been within the Vestfjord basin were sighted in fewer numbers, and then not sighted at all for several days. This result might indicate a wide-scale avoidance of the sonars used in the FLOTEX trials, as has been argued by some environmental groups, but it is impossible from a single observation to exclude the possibility that the whales' movements were instead driven by natural causes. In fact, whale numbers and distribution in the Vestfjord area have been changing in recent years, likely as a consequence of changes in the distribution of over-wintering herring out of the Vestfjord basin.

For the experimental behavioral-response (BRS) component of the pilot study, we successfully Dtagged 6 killer whales, and conducted 3 experiments: one 6-7 kHz sonar playback on two Dtagged animals, one 1-2 kHz playback, and one no-sound vessel approach. Reduced presence of whales in Vestfjord during the herring over-wintering season limited our ability to find new groups of whales to study, driving our decision to change research efforts to the summer months. Longer days during

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summer also make it possible to expose a single tagged subject to multiple sound types – helping control for individual variation in behavioral response to sonar sounds.

While results from only two sonar playbacks must be considered highly preliminary, we observed a striking difference in behavioral change during the exposures to two different sonar frequencies. We found no apparent change in behavior or travel direction of a travelling killer whale when it was exposed to a 1-2 kHz sonar signal with an unweighted cumulative sound exposure of ~177dB re $1\mu Pa^2$ s and maximum single pulse received levels of 154dB re 1μPa. In stark contrast, during a 6-7 kHz test, two simultaneously-tagged killer whales (along with the entire feeding group) stopped feeding activities and moved away after a sound exposure of ~160dB re $1\mu Pa^2$ s, with maximum ping-by-ping received levels of 140dB re 1μPa. Given that cessation of feeding is likely to have a greater biologically-relevant impact than avoidance during travel, why might killer whales cease feeding during exposure to sounds of an intensity below that which showed no effect on travel behavior?

A plausible explanation that we are exploring in our current research program is the strong difference in hearing sensitivity of killer whales at the two sonar frequencies. Using all available hearing data from captive animals, our research team produced a composite killer hearing curve (Fig 1). It can be clearly seen that killer whale hearing seems to be >25dB less sensitive at 1-2 than at 6-7 kHz. Exposure levels analyzed relative to this curve in fact reveal that the "sensation levels" of the 6-7 kHz sonar at the time of the behavioral change in fact exceeded those of the total 1-2 kHz exposure. The term "sensation level" refers not to absolute intensity of a sound, but intensity relative to the hearing threshold for that sound for a given individual. The sound level corresponding to the onset of temporary threshold shift appears to well described using sensation level as a metric (Kastak et al., 2007), and acoustic criteria recommend use of sensation level to estimate physiological impacts on hearing (Southall et al., 2007). However, the specific influence of hearing sensitivity on the risk of *behavioral* effects has never been directly assessed.

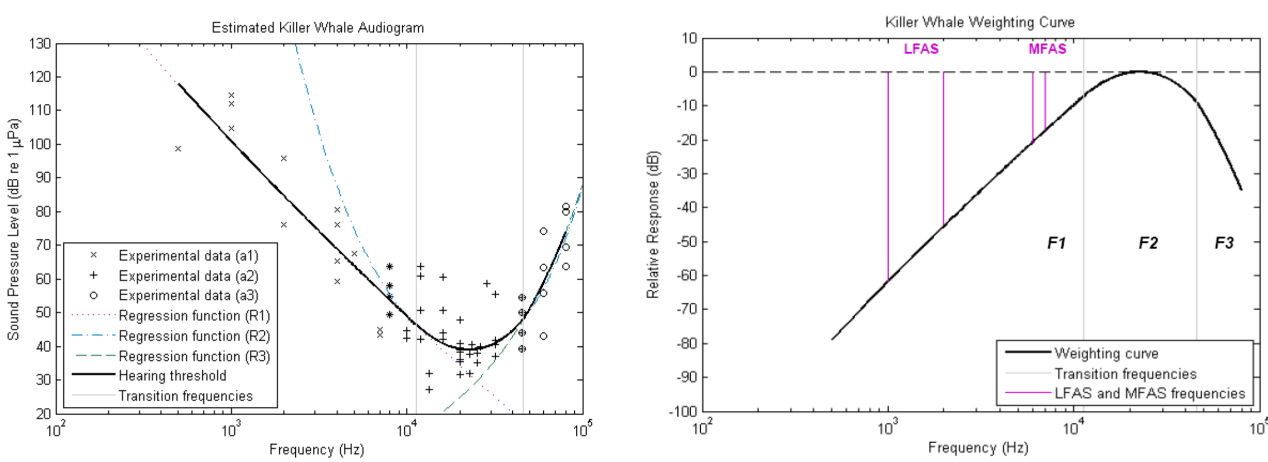

Figure 1. Left: An estimated audiogram for the killer whale using non-linear regression on all published hearing threshold data. Three separate functions were fit over the full frequency range of killer whale hearing. Right: weighting curves to convert received levels to "sensation levels" weighted by the hearing threshold. Note that killer whales have reduced hearing sensitivity to the 1-2 kHz "LFAS" signal compared to the 6-7 kHz "MFAS" signal. Figure courtesy of TNO.

OBJECTIVES

The current research program, begun 01 July 2008, seeks to build on the results from the 2006 pilot study to more fully quantify behavioral response of cetaceans to sonar as a function of the frequency band utilized by the sonar. A second objective of the research program is to continue to monitor the movements and behavior of killer whales in relation to future FLOTEX naval exercises, if possible. The project is motivated both by the applied need to assess the environmental impact of a new lower-frequency sonar system and the basic science question of the influence of sonar frequency on behavioral effects on marine mammals. We seek to test the prediction that the aversive-ness, or behavioral impact, of a sound should be influenced by the hearing sensitivities of species at the relevant sonar frequency. For species where little information is available on hearing sensitivities, behavioral responsiveness as a function of frequency will provide quantitative data on the effect of frequency. For species for which hearing sensitivities have been studied (or will be in the future), the results of this research can be directly interpreted in relation to sensation level as defined above.

APPROACH

Our primary approach is to conduct controlled presentations of military sonar signal sequences in blocks at 2 different frequencies (1-2 kHz and 6-7 kHz), and relevant control sounds, while observing their behavior using tags, towed hydrophone arrays, and visual observations. Specific research tasks are: 1) Determination of behavioral response thresholds by approaching a tagged whale while transmitting sonar signals. Each tagged whale will be sequentially tested at both sonar frequencies, in random order, with no-sound approaches or playback of killer-whale calls included as practicable as negative and positive controls*;* 2) Description of behavior during sonar exposures versus baseline and controls, and interpretation of the biological significance of any observed behavioral change. Careful monitoring and mitigation protocols are followed to minimize risk of harm to all research subjects; 3) Exploration of how response thresholds vary at different sonar frequencies, and in relation to reported hearing thresholds at the tested frequencies. Because we have better data on hearing sensitivity for killer whales, they are the primary study species, though we will also opportunistically study pilot and minke whales as well as other deep-diving odontocetes including the sperm whale. This diversity in target species is driven by the need to operate during the summer months when killer whales are quite widely dispersed in the study area off Northern Norway.

The research is carried out by an international collaborative team from the Sea Mammal Research Unit (SMRU), Woods Hole Oceanographic Institution (WHOI), Norwegian Defense Research Establishment (FFI), Institute of Marine Research (IMR), and Netherlands Organization for Applied Scientific Research (TNO). SMRU is home to PI Patrick Miller. WHOI is providing scientific advice from Dr. Peter Tyack as well as the provision of version 2 Dtags. Project management and logistic support, including acquisition of all research vessels and permitting are managed through FFI, led by Dr. Petter Kvadsheim. FFI also provides biological and tagging expertise, including the development of a new pneumatic launching system for the Dtag, headed by Lars Kleivane. TNO contributes to the effort by providing an advanced towed array system for recording and detecting marine mammal sounds (Delphinus), a multi-purpose towed source (Socrates), and staffing during the cruises under the leadership of Frans-Peter Lam and Frank Benders, with collaboration from René Dekeling of the Royal Netherlands Navy. The Socrates source system is capable of transmitting 1-2 kHz signals at a source level of 214dB re1µPa @1m, and 6-7kHz signals at a source level of 197dB re1µPa @1m. IMR provides scientific advice related to the presence of fish, primarily herring, prey of killer whales and other marine mammals.

WORK COMPLETED

To date, we have conducted one collaborative research cruise (“3S-08”) from 15 May to 11 June, with joint funding from Office of Naval Research, The Royal Norwegian Navy, the Royal Netherlands Navy, and the Norwegian Research Council. The primary tasks carried out on the 3S-08 cruise were to: 1.) tag several species of cetaceans with sensors recording behavior (Dtag), and thereafter carry out controlled exposure experiments (CEE) where the tagged animals are exposed to acoustic LFAS and MFAS signals. 2. Carry out control experiments in which tagged animals are either approached by the sonar ship but without any active transmission, or exposed to a playback of killer whale sounds. 3. Expose herring that is feeding in the area to LFAS, MFAS and orca signals while monitoring behavior of the herring using a fisheries sonar. Additional research included collection of CTD data in the study area, and collection of baseline behavioral observations of the marine mammals under study.


Figure 2. Left: The MS Strønstad shown with a VHF tracking array (top right) and towed hydrophone array. Visual observers were stationed on the flying bridge. Right: The aft deck of the HU Sverdrup II showing the tow cable for the Socrates source, and a pilot whale surfacing nearby.

The research was conducted off two vessels, the HU Sverdrup II which carried the Socrates source, and the MS Strønstad which was used to track the tagged whale(s) (Fig. 2). Each of the two vessels also carried a tagging boat. Tagging was conducted using a standard system, and also a pneumatic tag launching system newly developed by FFI. Rigorous testing of the forces applied to the tag during launch suggested that use would be safe with the Dtag, but a test-Dtag package containing a TDR of identical weight and size to the Dtag was used in initial tests.

RESULTS

The data collection effort during the 3S-08 cruise was highly successful. We made a total of 19 tag attachments: 3 on sperm whales, 1 on a killer whale, and 15 on pilot whales. Of these 19 tag deployments, 13 were of Dtags using the pole system. Of the six tags deployed with the pneumatic launch system, 3 were of the test-Dtag TDR, and 3 were with the Dtag. One Dtag was lost after deployment on a sperm whale. FFI received aid from a Marine Patrol Aircraft which detected a Dtag onboard the Sverdrup at 25nm, but no signal was ever detected from the lost Dtag.

From these 19 tag deployments, a total of 6 sonar exposure experiment cycles were conducted (Table I). These 6 experiments comprised a total of 6 LFAS, 7 MFAS, 4 Silent Approach, and 2 killer whale (*orca*) feeding sound playbacks – as well as pre-exposure post-exposure periods.

Table I. Summary of behavioural response experiments conducted during the 3S-08 research cruise.

Date	Dtag data set	Species	Exposure sequence	comments
28 May	oo08_149a	*O. orca*	Pre-exposure, MFAS, post-exposure 1, LFAS, post-exposure 2, Silent Approach, post-exposure 3, *orca*, MFAS2, post-exposure 4	Unable to approach closely on first MFAS and LFAS
29 May	gm08_150c	*G. melas*	Pre-exposure, MFAS, post-exposure 1, LFAS, post-exposure 2	Tag off before silent approach
31 May	pm08_152a	*P. macro.*	Pre-exposure, MFAS, post-exposure 1, LFAS, post-exposure 2	Tag off before silent approach
03 June	gm08_154d	*G. melas*	Pre-exposure, LFAS, post-exposure 1, MFAS, post-exposure 2, Silent Approach, post-exposure 3	
06 June	gm08_158b	*G. melas*	Pre-exposure, Silent Approach, post-exposure 1, LFAS, post-exposure 2, MFAS, post-exposure 3	Dtag data lost due to battery failure
07 June	gm08_159a	*G. melas*	Pre-exposure, Silent Approach, post-exposure 1, LFAS, post-exposure 2, MFAS, post-exposure 3, *orca*, post-exposure 4	

The controlled sonar exposures were conducted very successfully, with the source vessel able to approach to within <1km of the tagged whale in almost all cases. The quality of the data collected during the experiments is high, with the exception of the failure of the Dtag on the experiment of 06 June. The tag was found to be infiltrated with seawater, and was subsequently repaired. All other Dtag data sets are of high quality, both in acoustic and sensor data sets (Fig 3, left). In addition to the Dtag, each subject was monitored visually and with a towed array from the tracking vessel Strønstad. To aid in synchronizing the Dtag data sets to the sonar exposures, each Dtag was returned to the HU Sverdup II while still recording, and a set of calibration pings were recorded by it (Fig 3, right).

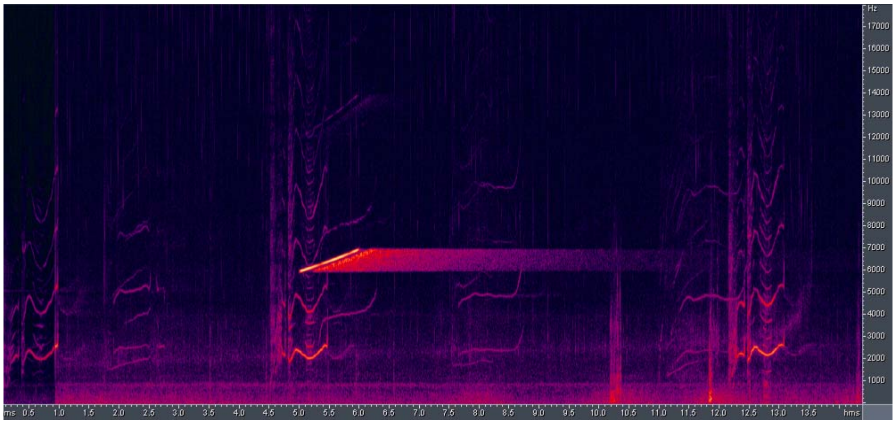

Figure 3. Left: High SNR Dtag recording of 6-7 kHz sonar during vocal exchange of pilot whales. Right: PI Patrick Miller synchronizing Dtag to Socrates followed the 3rd experiment.

At the time of this report, work is ongoing to complete the following analyses:

• measure received levels of the sonar transmissions at the whale. The acoustic received levels will be calculated as acoustic intensity re 1μPa, and as a cumulative exposure level both unweighted, and weighted relative to the hearing threshold of species for which hearing threshold data exists;

• measure the distance from the source to the subject whale, using visual tracking and acoustic data;

• quantify behavioral variables of each tagged whale including horizontal movement, diving behavior, acoustic calling and echolocation behavior, and 3-dimensional movements including orientation and swimming movements (see figure 4 for example);

• baseline and pre-exposure observations will be used to specify the biological relevance of behaviors recorded by the Dtag;

• using each whale as its own control, we will assess whether a behavioral change occurred during each exposure period, and at what acoustic exposure level;

• the characteristics of any behavioral change will be carefully described;

• results across different subject and species will be integrated to calculate the probability of a behavioral reaction versus sound intensity and sonar signal frequency.

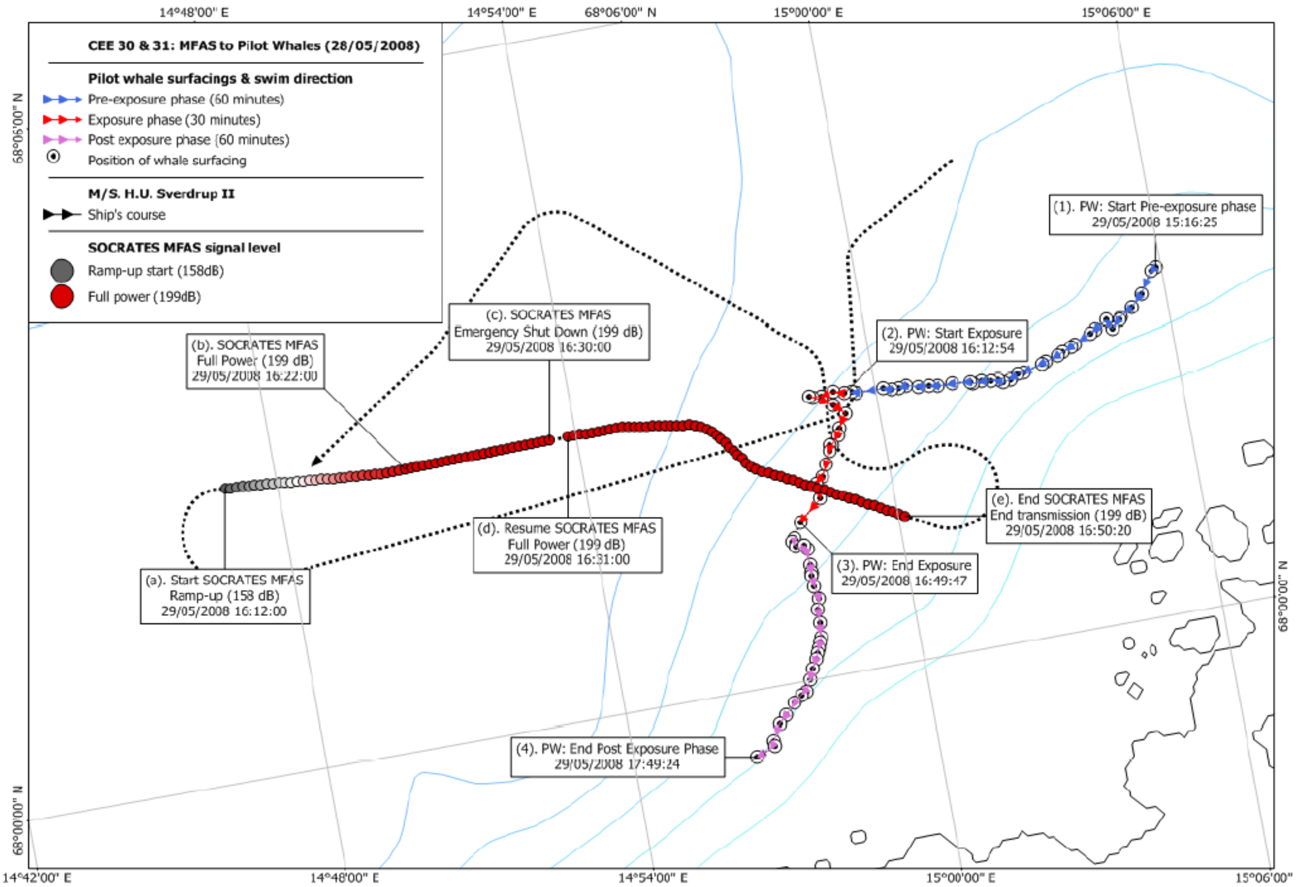

Figure 4. Geometry and timing of the MFAS exposure to whale subject gm08_150c. The whales positions are shown as filled circled, color-coded by the phase of the experiment. Note in this case, the whales made a strong turn away from the source boat HU Sverdrup II, which was approaching them directly from the front.

RELATED PROJECTS

A study of behavioural responsiveness of beaked whales and other deep-divers to sonar signals and killer whale playbacks in ongoing in the AUTEC range. Both projects have conducted behavioural response tests to pilot whales, and we plan to coordinate our data analysis activities so that the results of both studies can be integrated as well as possible.

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